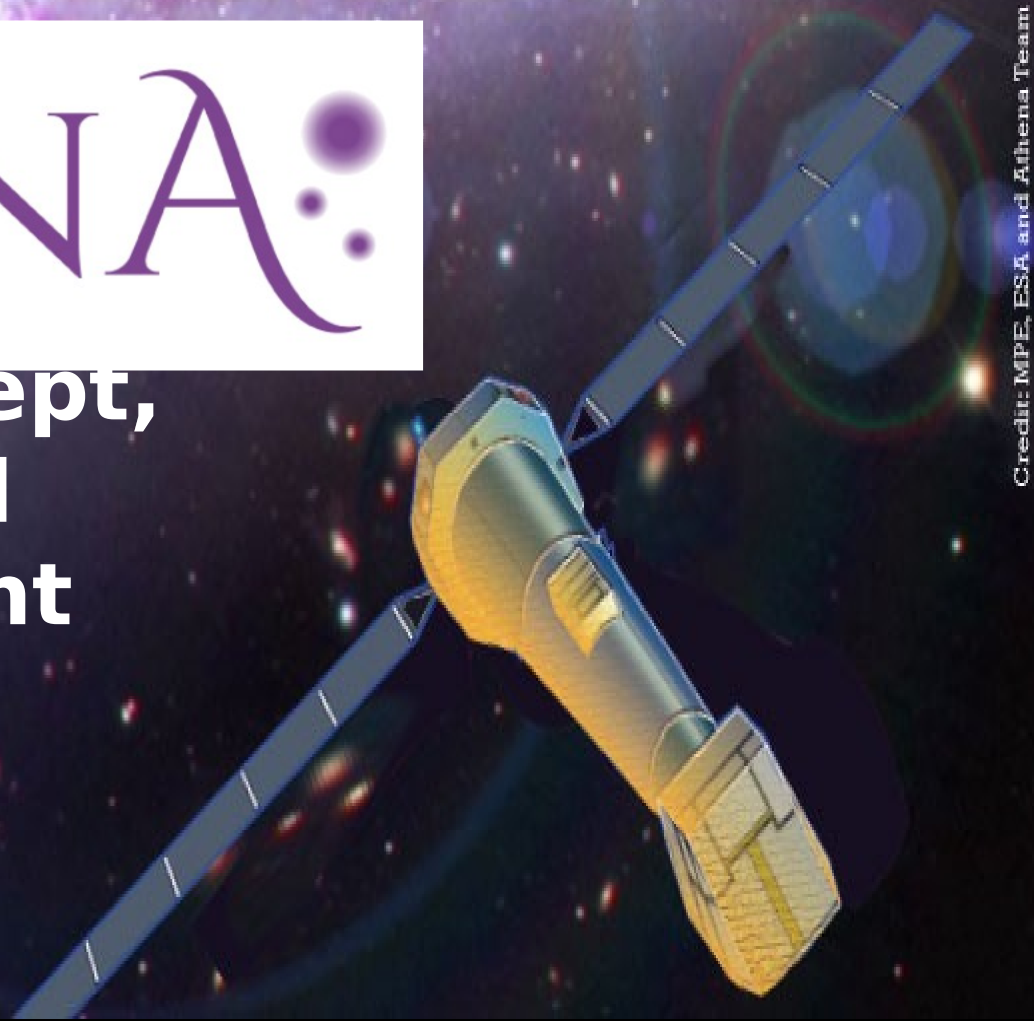
ATHENA

Mission Concept, Status and Development



Laura Brenneman (SAO)

On behalf of the ATHENA Science Study Team and Working Group Chairs

European Space Agency

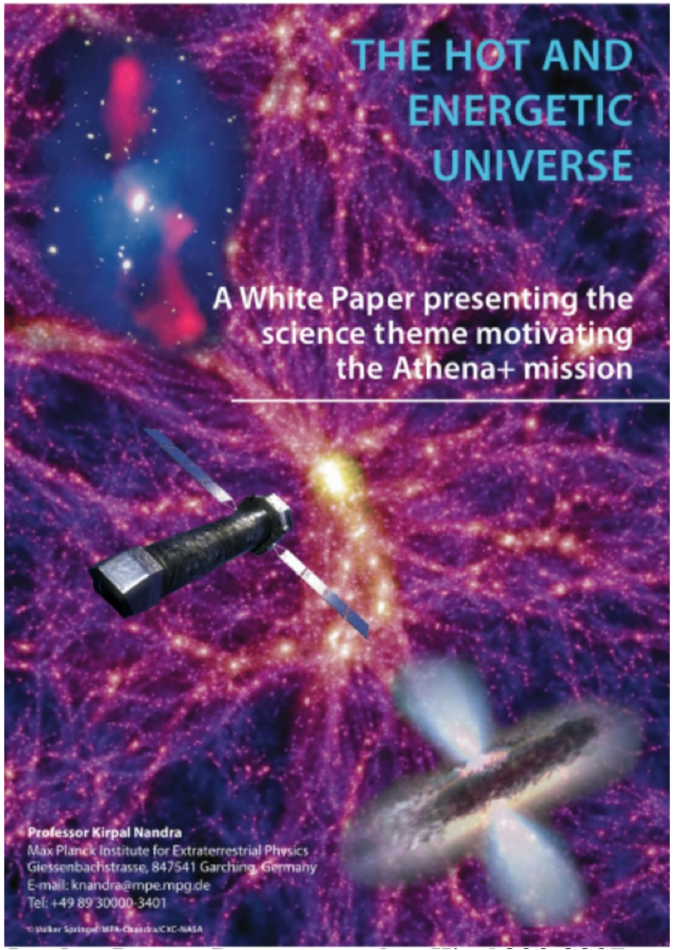
Advanced Telescope for High Energy Astrophysics

- **Second large (L2) mission** of ESA's Cosmic Vision, 2015-2035
- **Science theme: The Hot and Energetic Universe**
  - How does ordinary matter assemble into large-scale structures?
  - How do black holes grow and influence their surroundings?
- Also provides **observatory science across all corners of Astrophysics**
- More info at:
  http://www.the-athena-x-ray-observatory.eu

The Hot and Energetic Universe

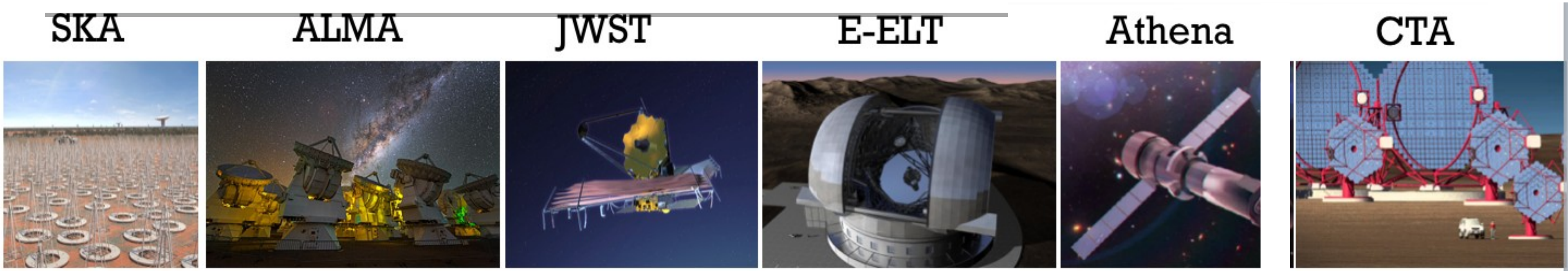
- **The Hot Universe:** How does the ordinary matter assemble into the large-scale structures we see today?
  - 50% of the baryons today are in a hot (>10^6 K) phase.
  - There are as many hot baryons in clusters as in stars over the entire Universe.

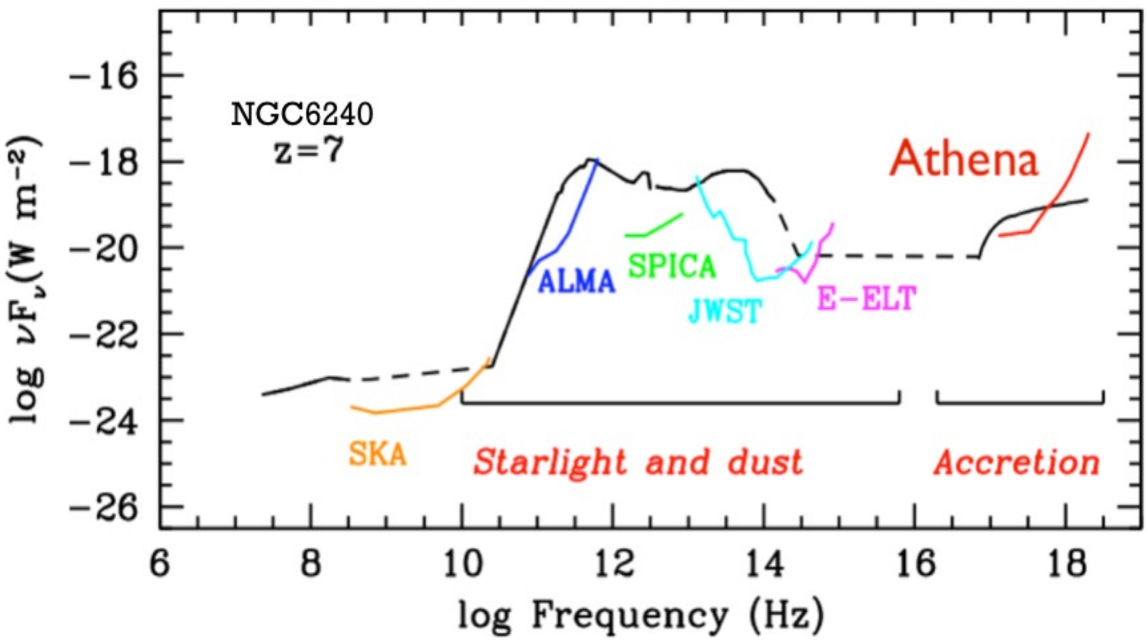
- **The Energetic Universe:** How do black holes grow and influence the ISM, IGM and ICM around them?
  - Building a SMBH releases ~30x the binding energy of its host galaxy.
  - 15% of the energy output in the Universe is in X-rays.



Nandra+ (2013)

The 2020’s Big Observatories Landscape





Courtesy of M.Türler (ISDC) and the ATHENA Science Study Team

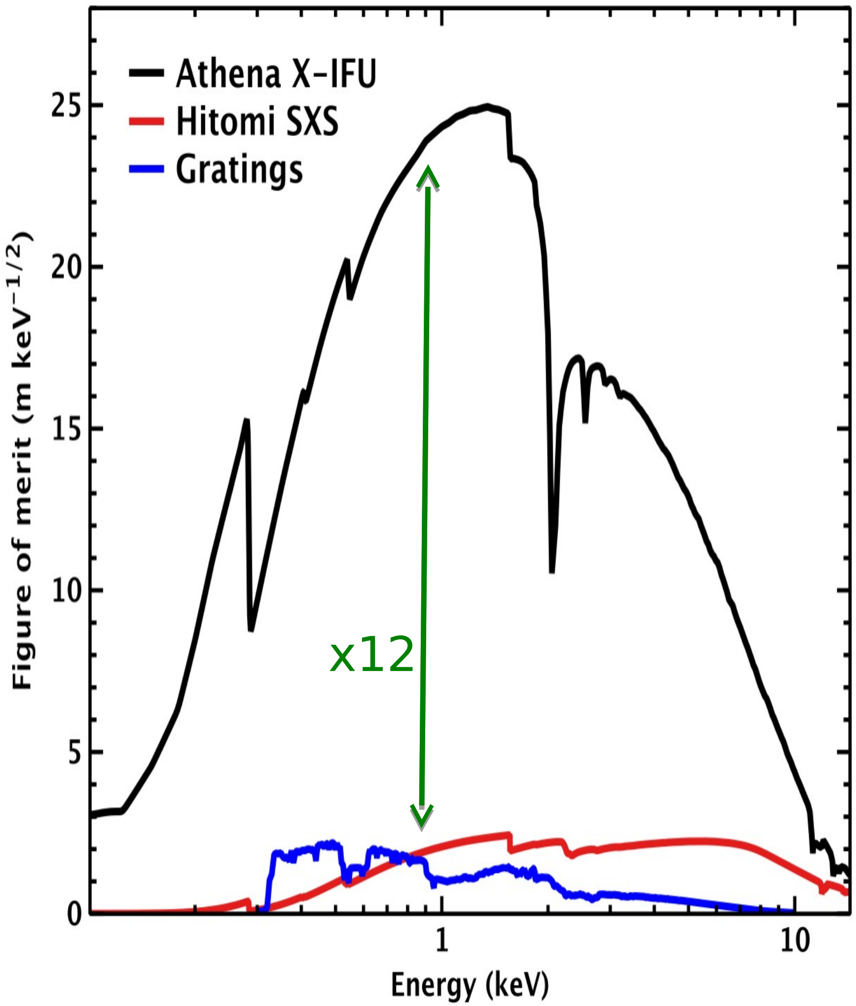
ATHENA Mission Profile

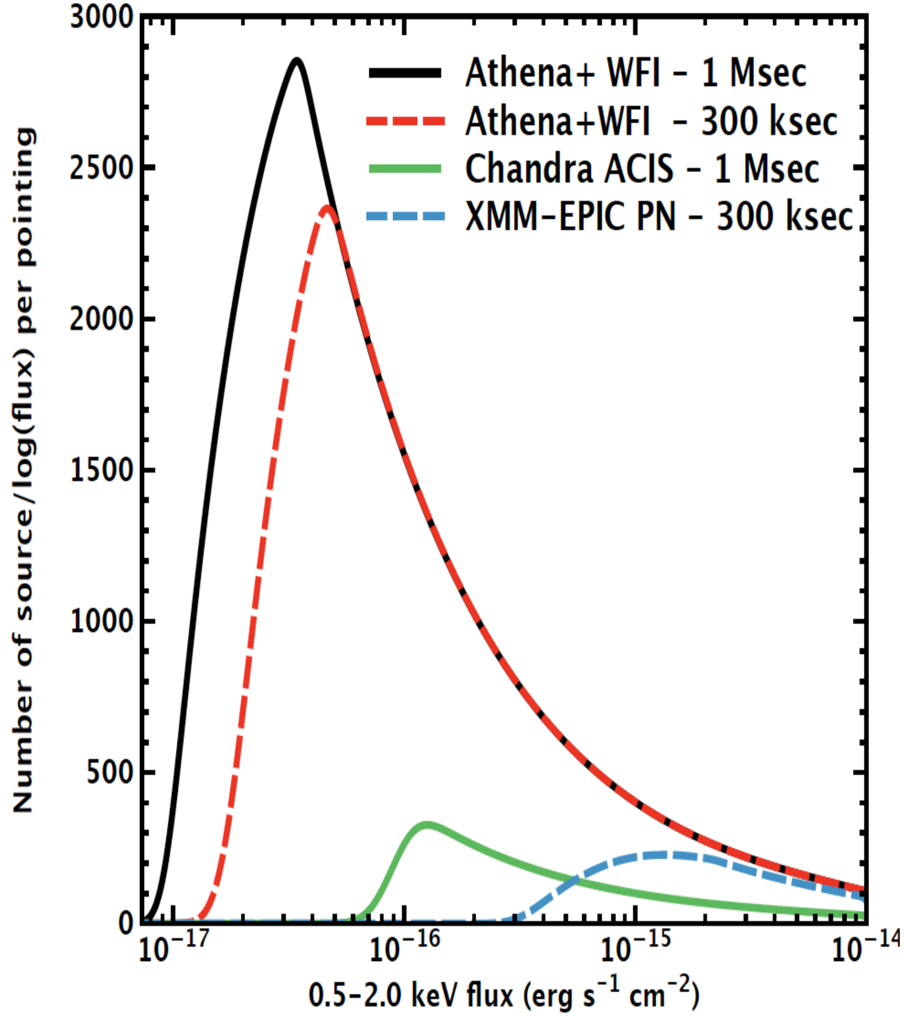
- Single telescope, Silicon Pore Optics (SPO) technology, 12m focal length, $2m^2$ area (goal) @1 keV.
- **WFI** (Active Pixel Sensor Si detector): wide-field (40'x40') spectral-imaging, CCD-like energy resolution (~150 eV @6 keV).
- **X-IFU** (micro-calorimeter): 2.5 eV energy resolution, 5' diameter field-of-view, ~5" pixel size.
- Movable mirror assembly to switch between instruments in the focal plane.
- Defocusing capability increases count rate dynamical range.

ATHENA concept, ESA CDF

- Metrology system to achieve a reconstructed astrometric error ≤1" (3σ).
- **Launch 2028**, Ariane 6.4, L2 halo orbit (TBC).
- Nominal lifetime 4 years + extensions.

A Transformational Mix of Science Performance





Barret+ (2016), Nandra+ (2013)

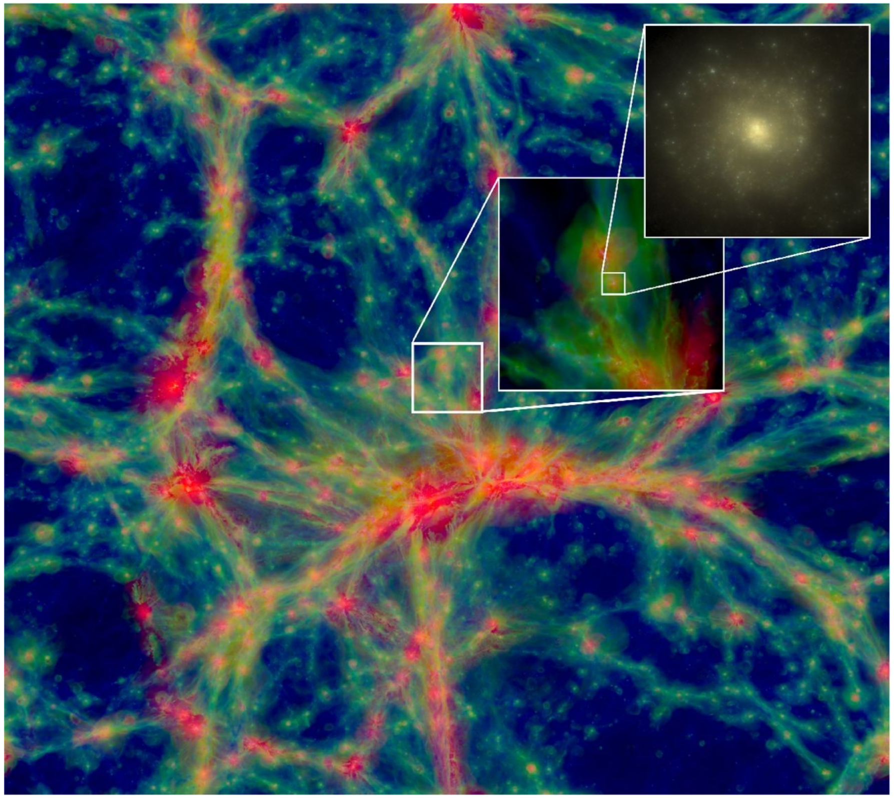
ATHENA Key Mission Requirements

- **Effective area:** 1.4 m^2 @1 keV (goal 2m^2), 0.25 m^2 @6 keV
- **Angular resolution:** 5” on-axis, 10” at 25’ off-axis
- **Energy range:** 0.2-12 keV
- **Instrument FoV:**
  - WFI = 40’
  - X-IFU = 5’
- **Spectral resolution:**
  - WFI = ~150 eV @6 keV
  - X-IFU = 2.5 eV @6 keV
- **Count rate capability:**
  - WFI = >1 Crab (fast chip)
  - X-IFU = 1 mCrab (2.5 eV, 80% eff.) with goal of 10 mCrab, 1 Crab (30 eV, 30% eff.)

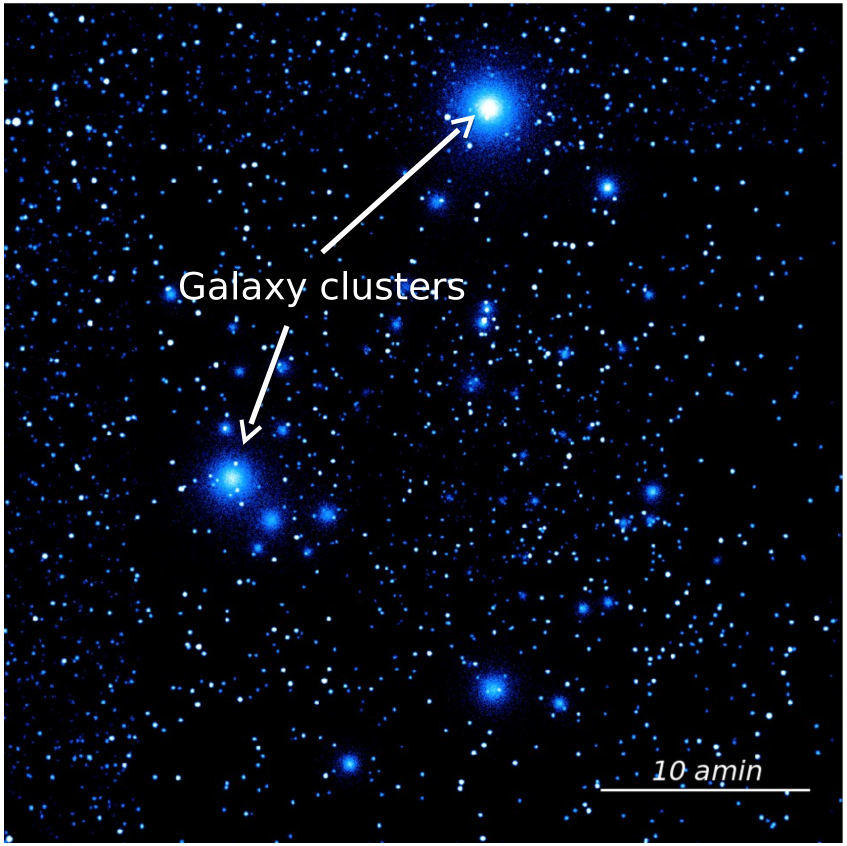
Science Instrument Module (SIM) design as of December 2016

(a.k.a. FPM) concept, ESA CDF

The Hot Universe: Baryonic Assembly

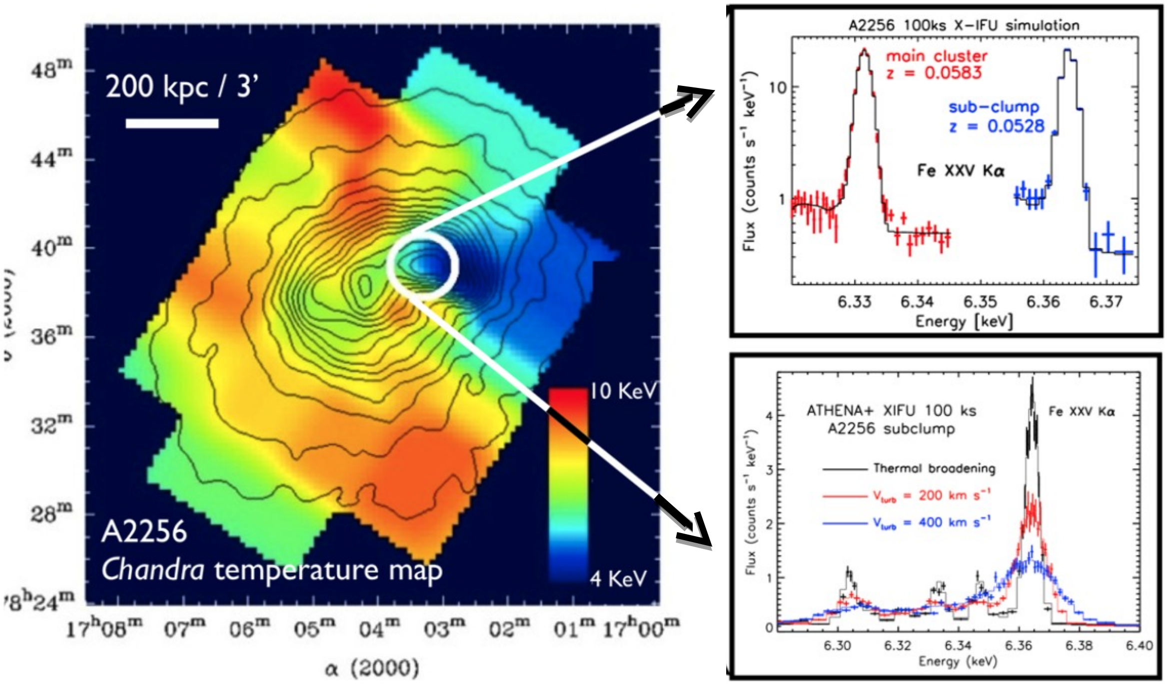


Schaye+ (2015)

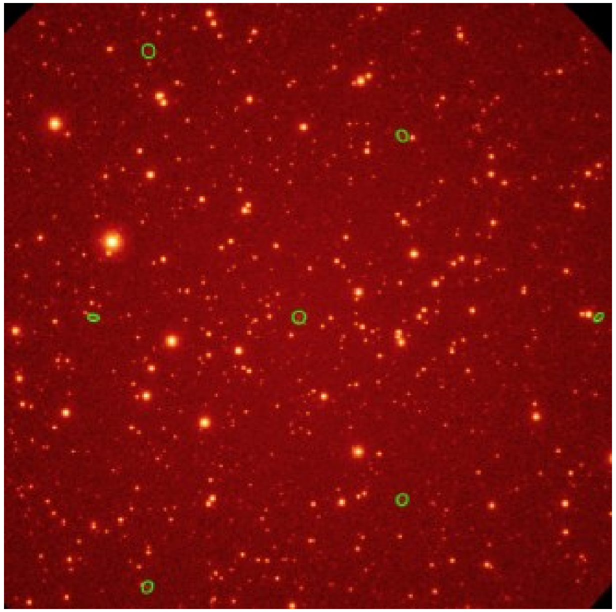


ATHENA/WFI 1Ms simulation (MPE & WFI team)

Early Galaxy Groups and Clusters



Ettori+ (2013), Pointecouteau+ (2013)



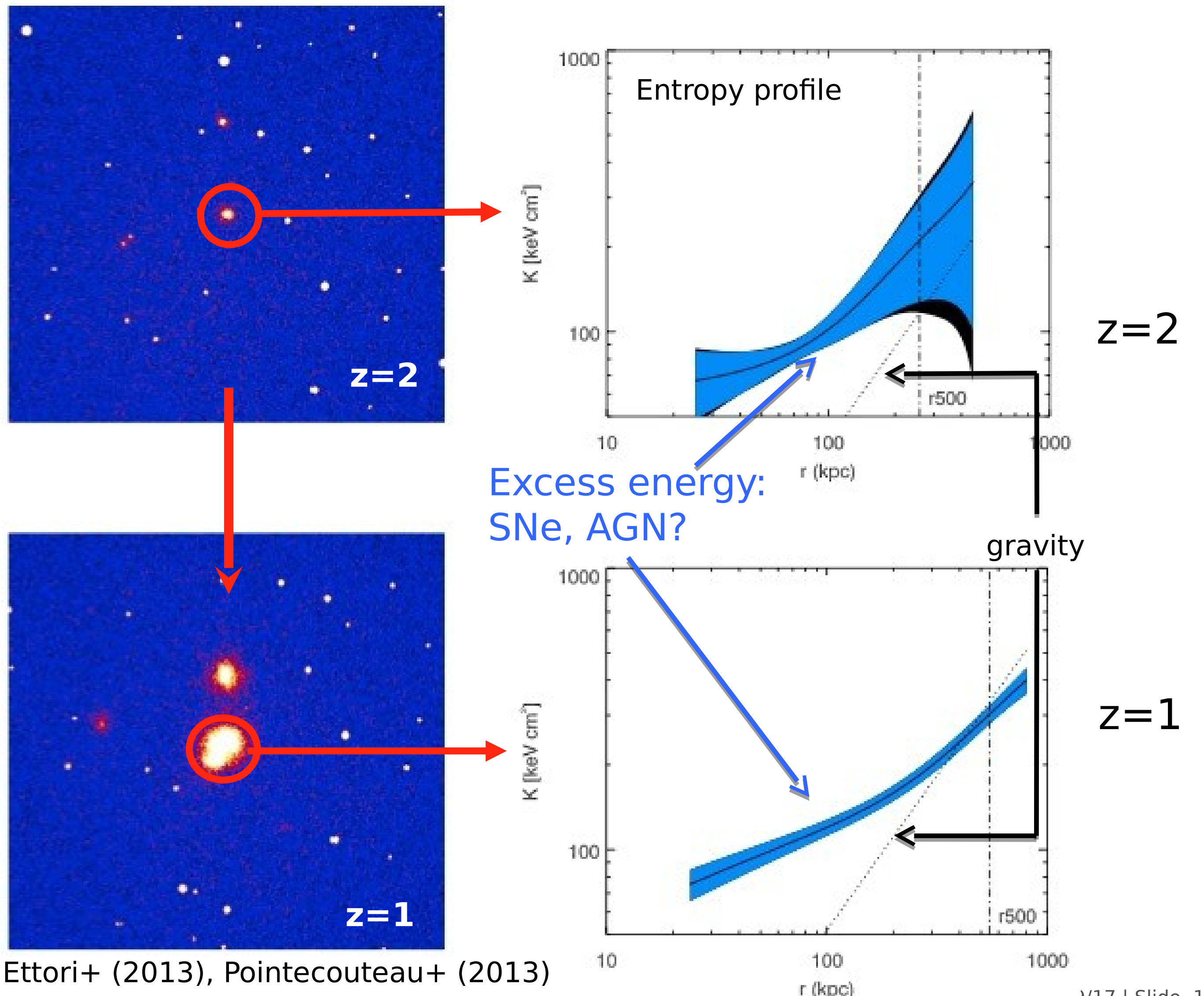
- Sub-clumps accreting onto clusters can be characterized: turbulent broadening from X-IFU line widths to <5%.
- Will inform our understanding of structure formation.

- Search for early galaxy groups M>5 x 10^{13} $M_\odot$ at z>2.
- Total of ~50 groups in multi-tiered survey lasting for ~1 year.

Thermal Evolution of Hot Cluster Gas

- **Energy deposition history** in ICM shows how SMBHs, stellar populations and hot gas co-evolve.

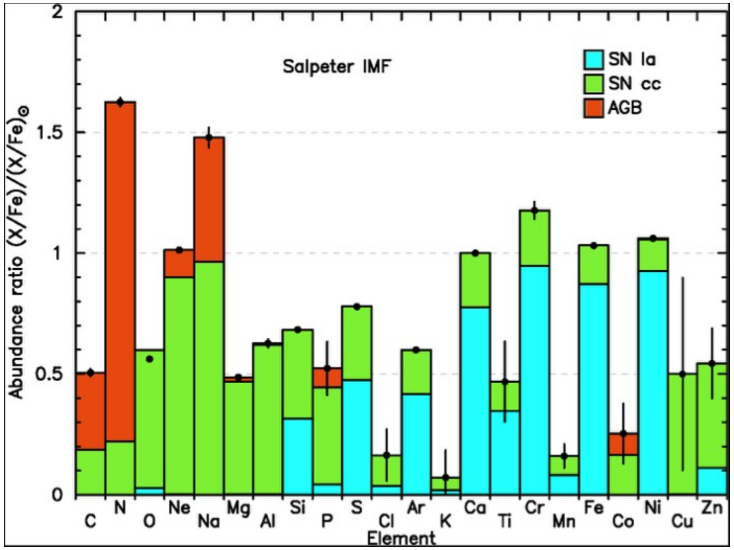
- Can trace **divergence from expected gravity-only entropy** profiles at small radii, how this evolves with redshift.

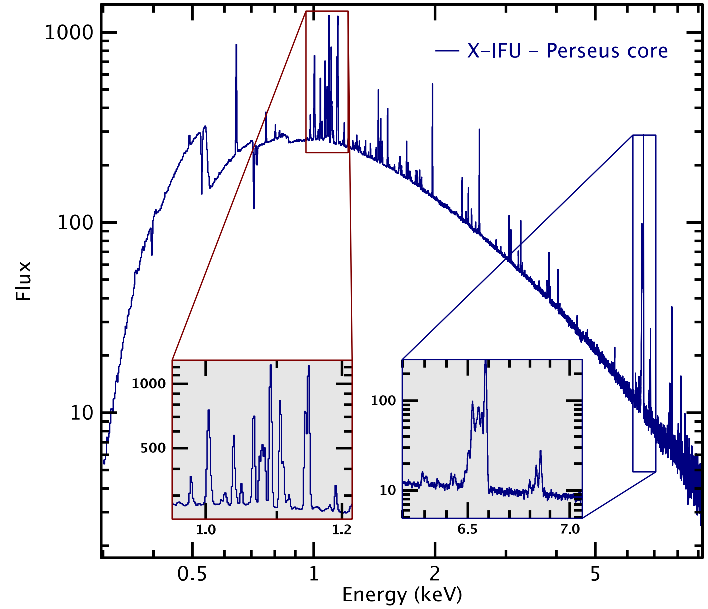


Ettori+ (2013), Pointecouteau+ (2013)

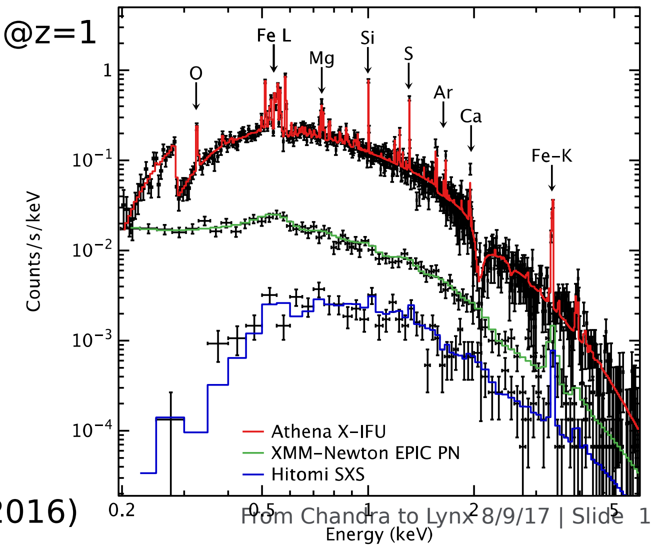
Cluster Chemical Evolution

- Clusters of galaxies are closed boxes, all gas is virialized in the DM potential well.
- Cosmic chemical evolution best traced by cluster gas.
- Constraints on SN types and IMF.





Galaxy group @z=1

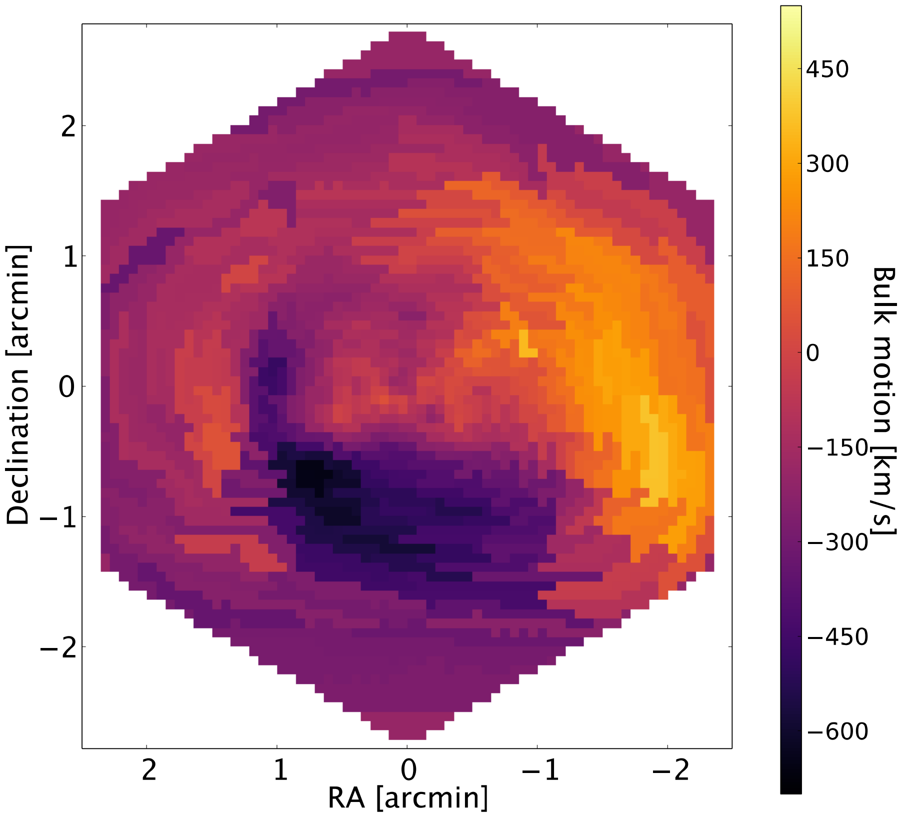


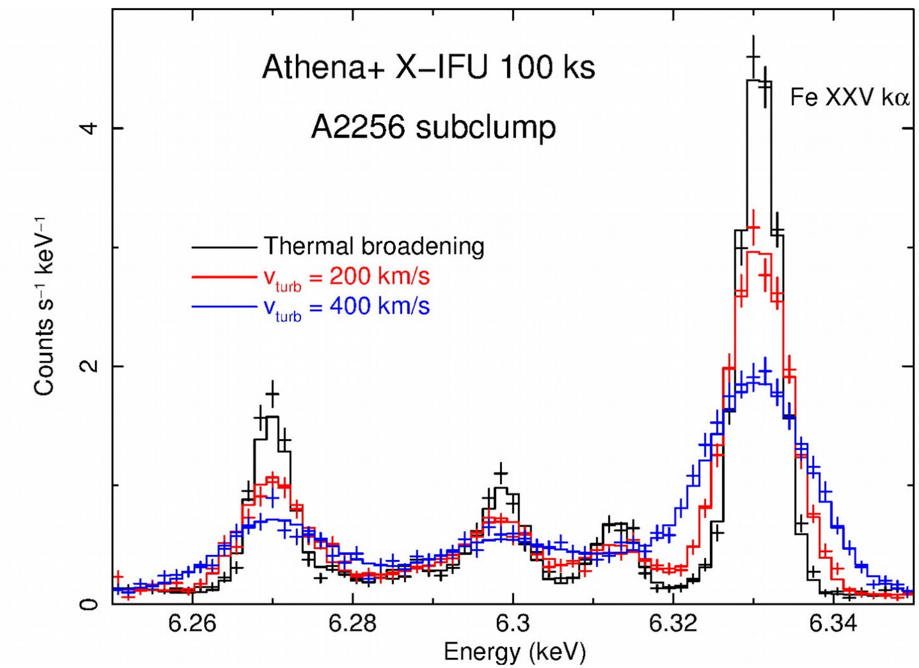
#ATHENANuggets by J. de Plaa

Barret+ (2016)

Cluster Bulk Motions & Turbulence

ATHENA will measure gas bulk motions and turbulence down to 20 km/s.





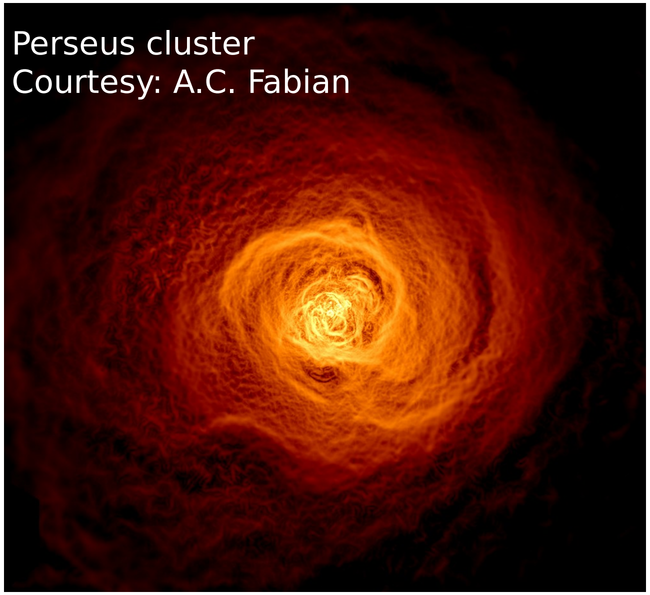
Ettori+ (2013), Pointecouteau+ (2013)

Courtesy: P. Peille, E. Pointecouteau, V. Biffi, E. Rasia, K. Dolag, S. Borgani, J. Wilms

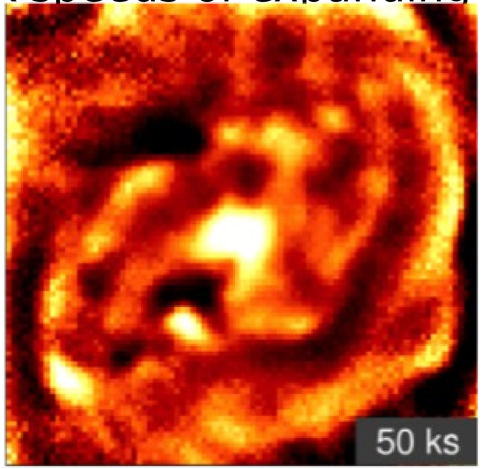
AGN Feedback on Cluster Scales

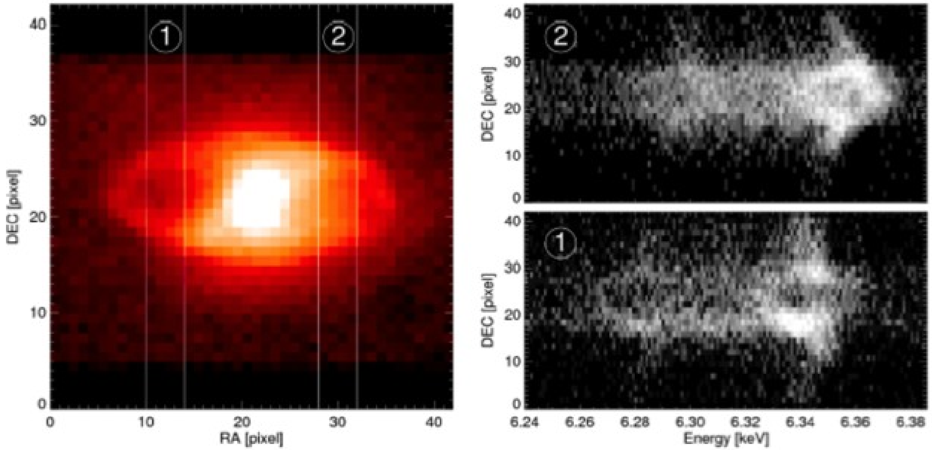
Dissipation of AGN energy into ICM:

- Energy stored in hot gas around bubbles via bulk motions and turbulence.
- History of radio cluster feedback via ripples.
- AGN jet fueling vs. cooling through temperature distribution.
- Shock speeds of expanding radio lobes.

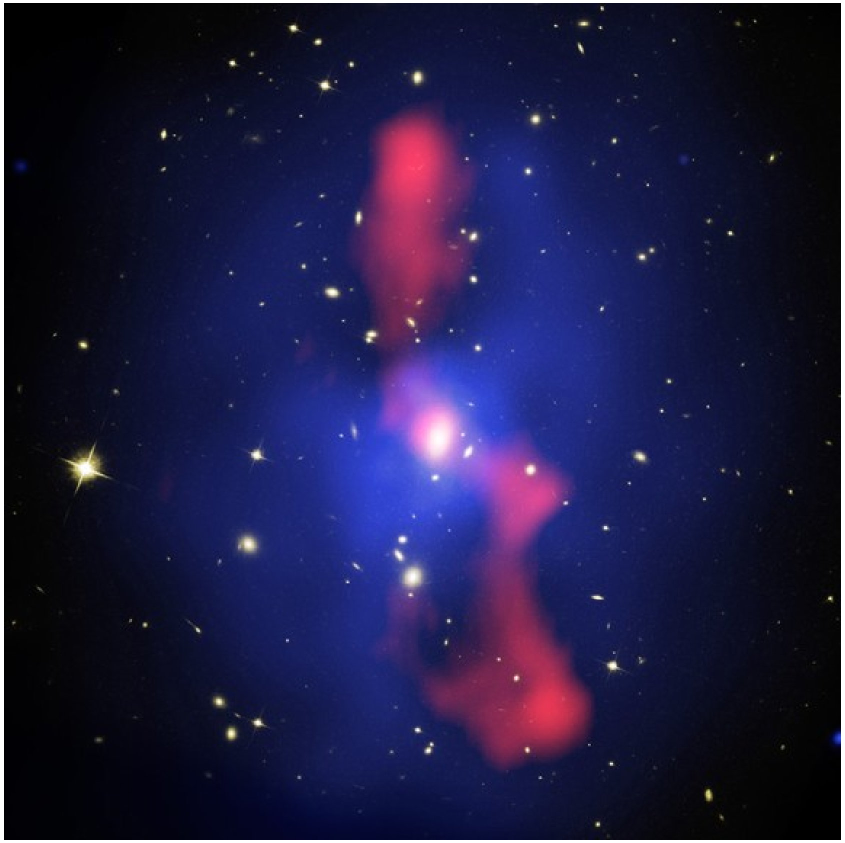


Croston+ (2013), simulations by S. Heinz

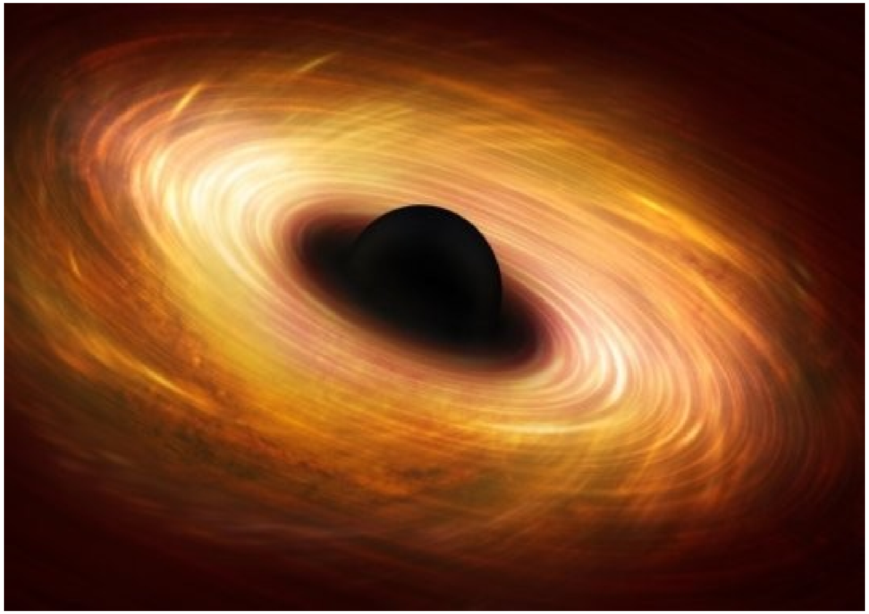




The Energetic Universe: Black Holes

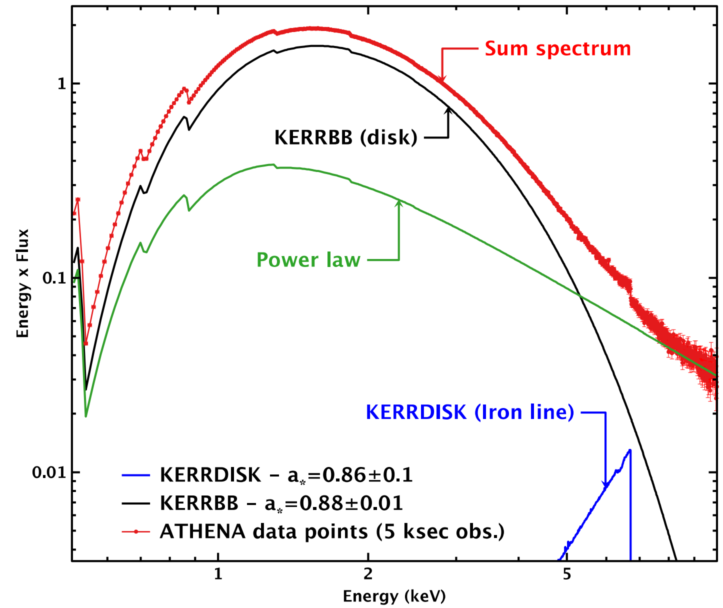


MS0735.6+7421 McNamara+ (2005)

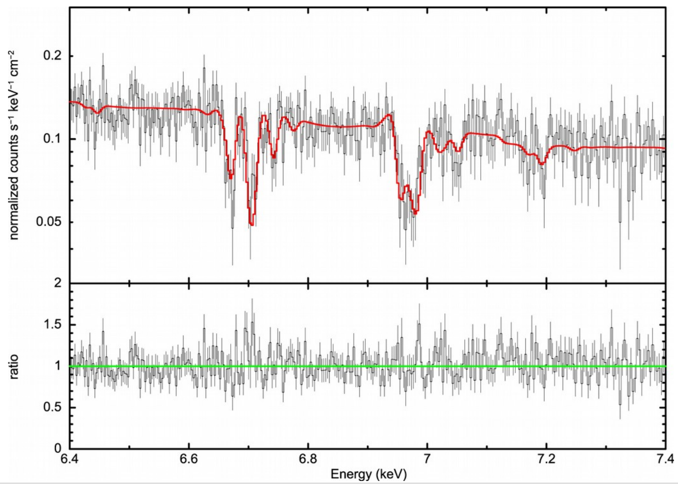


BHB and NS Accretion Physics

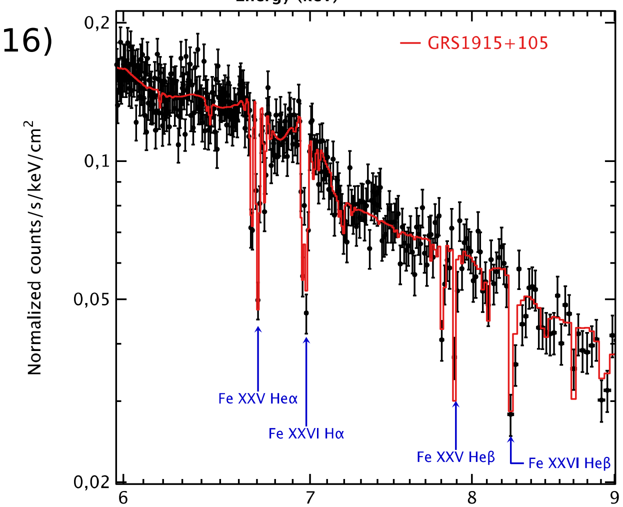
- **Measure BH spins**
  - Via continuum fit & Fe K line spectroscopy.
  - Constraints on SN origin & relation to jets.
- **Accretion geometry**
  - Disk truncation from lag spectra.
  - Winds as diagnostics of the accretion flow on ~100s timescales.



Barret+ (2016)

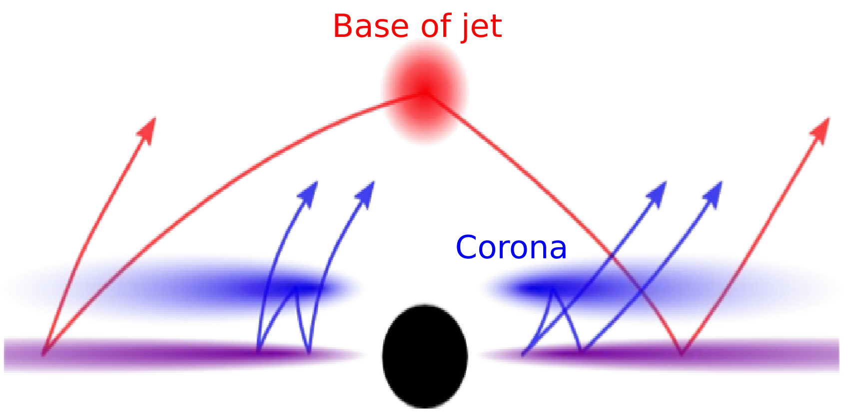


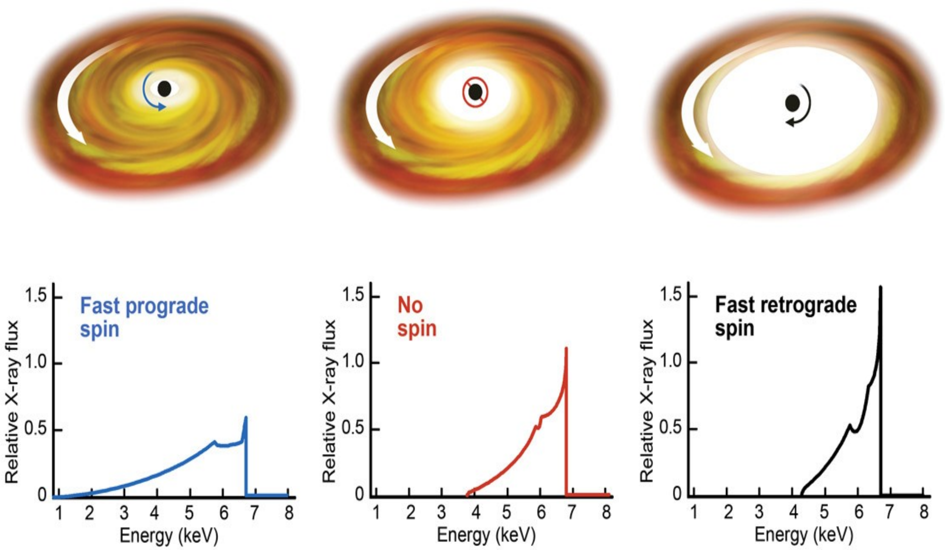
GRS1915
Miller+ (2016)

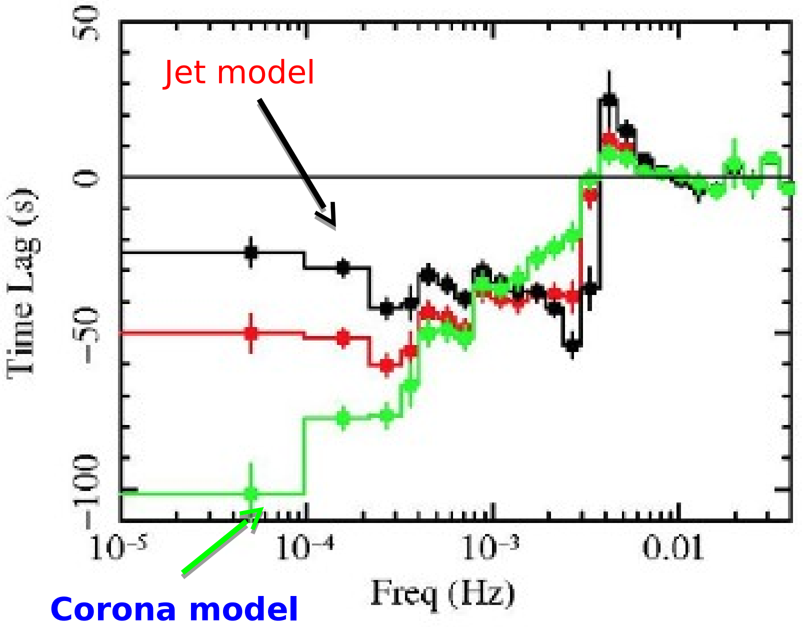


Supermassive Black Hole Physics

- **Measure SMBH spins** through Fe line spectroscopy.
- **Accretion geometry and jet/disk relation** through reverberation mapping.





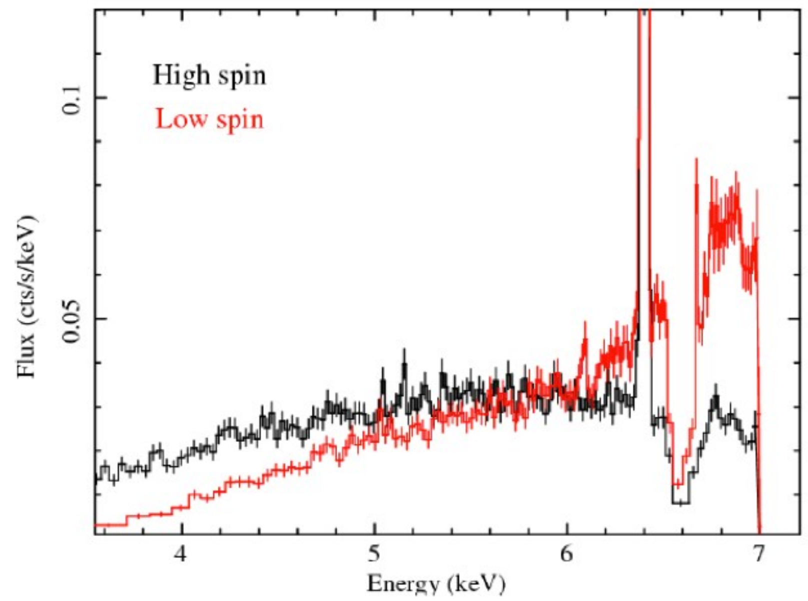


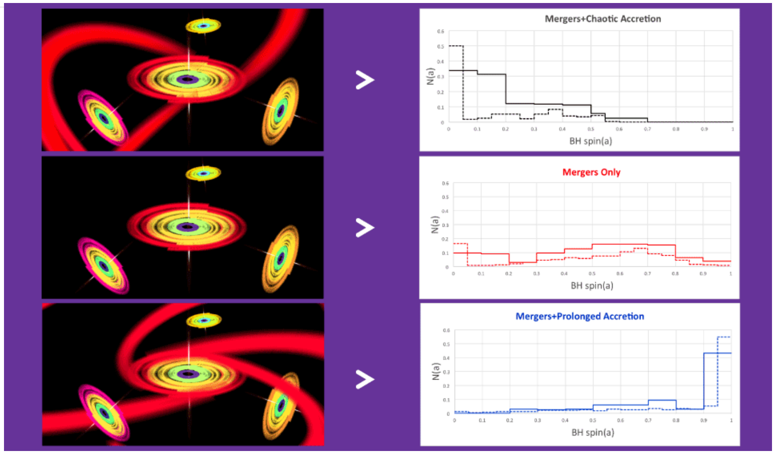
SMBH Growth: Accretion vs. Mergers

- **SMBH spin distribution is highly sensitive to SMBH growth history**
  - Prograde accretion spins up SMBH.
  - Mergers & chaotic accretion spin down SMBH.

- **A SMBH spin survey with ATHENA will reveal dominant SMBH growth mechanism**
  - Partly doable with XMM-Newton, except for removal of narrow features.

- **Biases: Highly spinning SMBH are radiatively more efficient, overrepresented in flux-limited samples** (Vasudevan+ 2016)
  - ATHENA can obtain spins for fainter sources and correct for this effect.

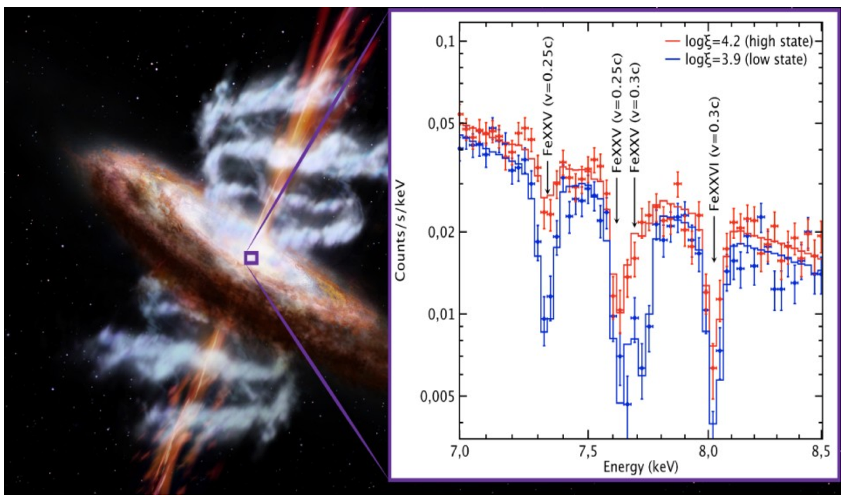




#ATHENANuggets by L. Brenneman & G. Miniutti

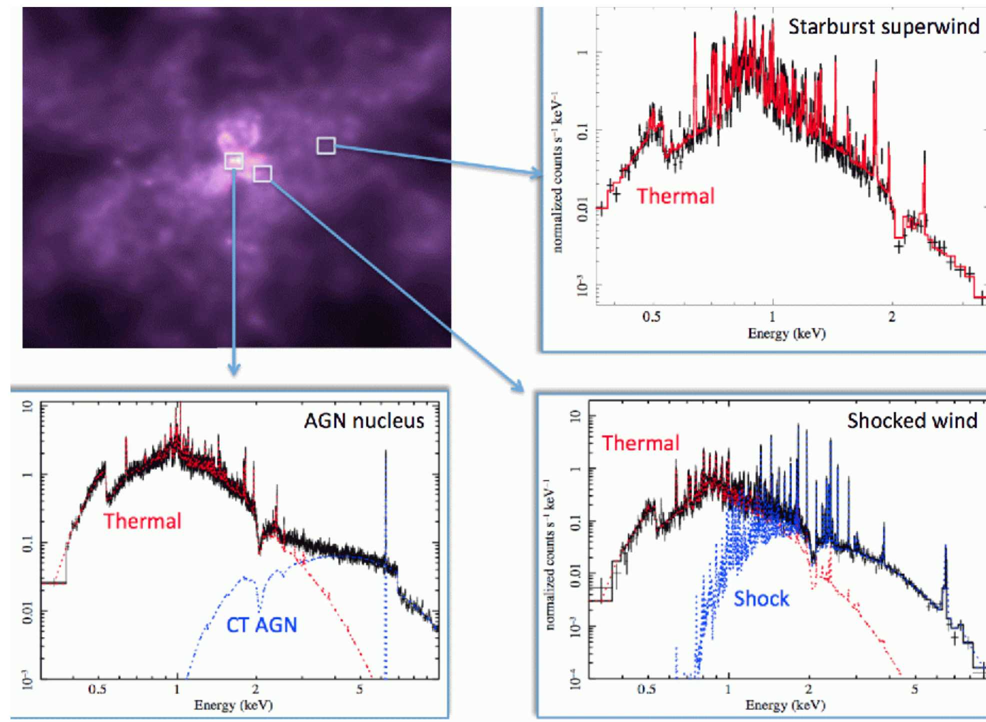
AGN Winds and Outflows

- **Mechanical feedback** effective if $L_{mech} > 1\% \, L_{bol.}$
- **Mechanical energy** released in ultra-fast outflows $\sim v^3$.



Cappi, Done+ (2013)

- **Gas, metals** and mechanical energy are ejected into the CGM by AGN and starbursts:

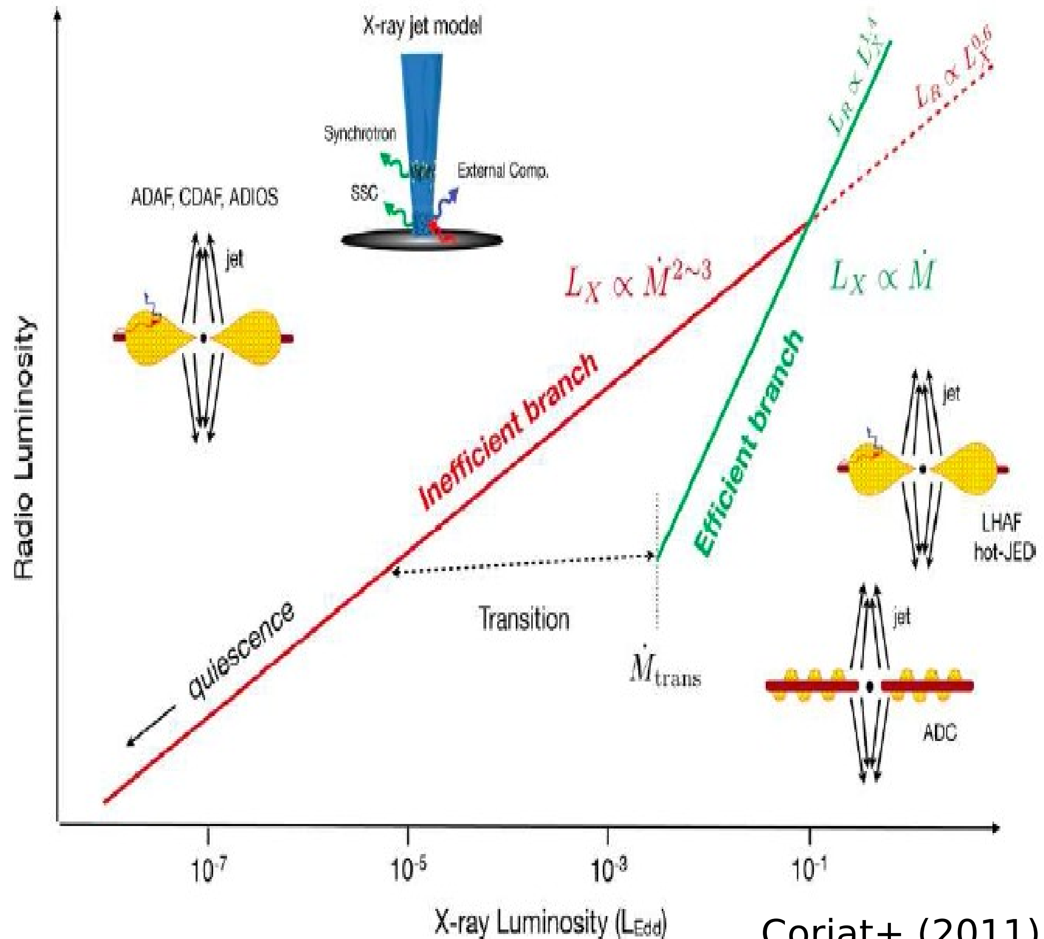


NGC 6240, M. Cappi+ (2013)

#ATHENANuggets by M. Cappi & G. Ponti

Jets, Winds & Outflows

- Relationship between **accretion** (X-rays) and **ejection** (X-rays for winds/outflows & radio for jets)
- **Variability correlation** studies (Radio/X-ray): jet-outflow co-existence.
- Test **jet-spin paradigm**.
- The **origin of radio emission in radio-quiet AGN** – needs SKA sensitivity:
  - Synchrotron emission from sub-relativistic jet
  - Free-free emission from corona



Coriat+ (2011)

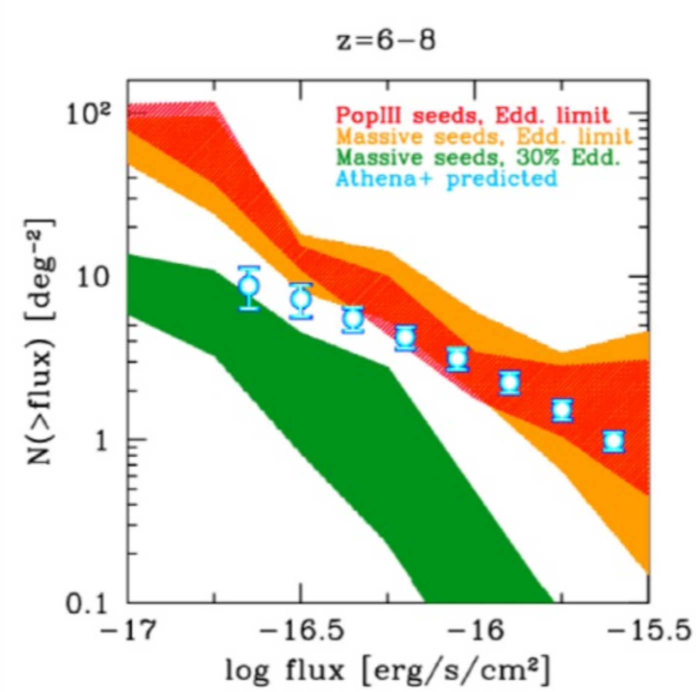
ATHENA Peering into the Dark Ages

- ATHENA plans to perform a **1-year multi-tiered survey** (~40 deg^2) aiming at:
  - Identifying ~few 100 AGN at z>6.
  - Census of the whole AGN population of z~1-3.
  - Finding 50 groups at z>2.

- It will find **600,000 AGN, down to ~10^{-17} erg cm^{-2} s^{-1}**.

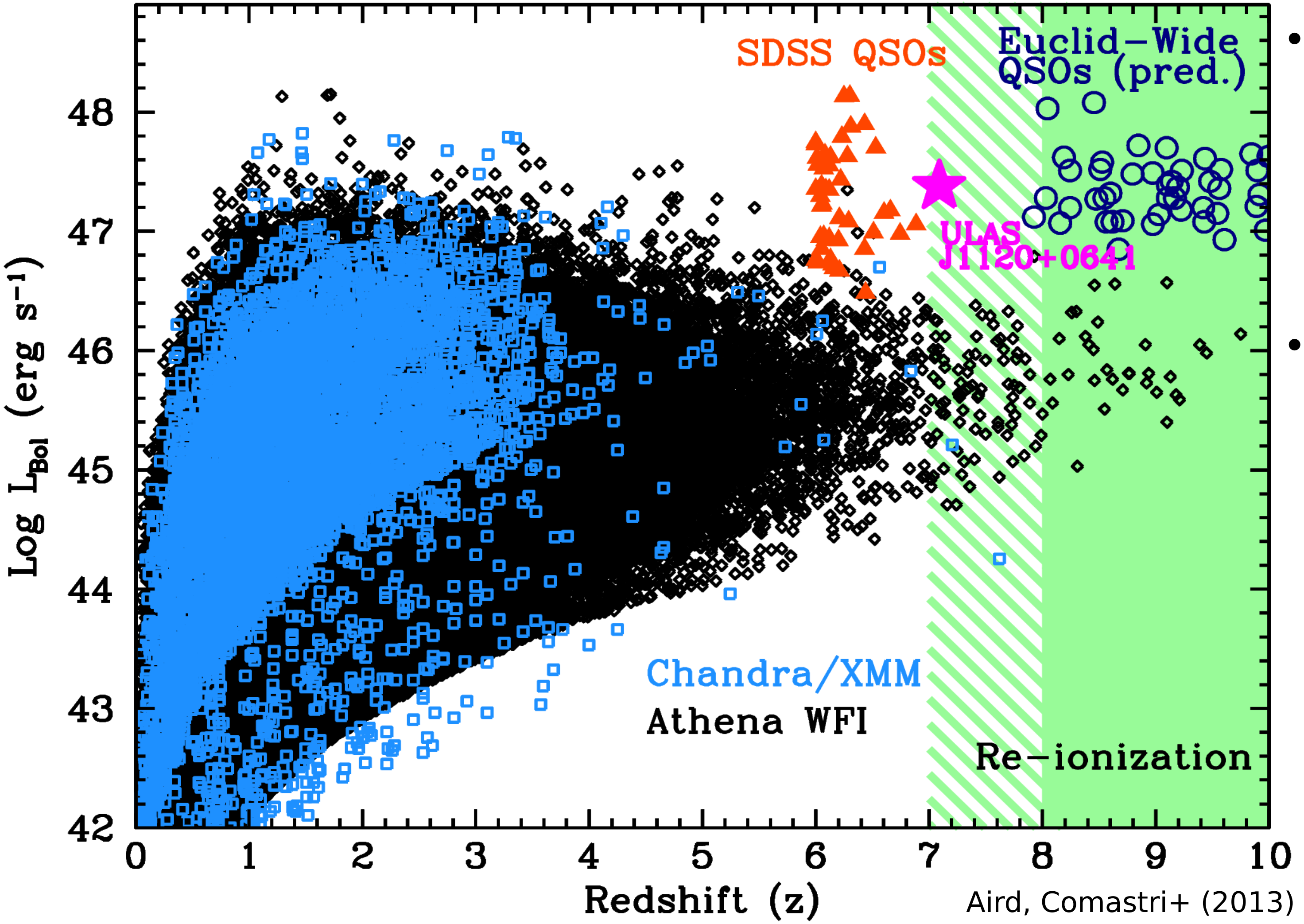
- **Probe early phases of SMBH growth and SMBH seed masses.**

Aird, Comastri+ (2013)



- Obtain counterparts and z (IFU & ALMA).
- ISM masses (ALMA).
- Stellar masses, SMBH masses & SFR (AO NIR/MIR spectroscopy).
- Full survey characterization: 4MOST, MOONS, ELT-MOS, etc.

The History of SMBH Growth



Aird, Comastri+ (2013)

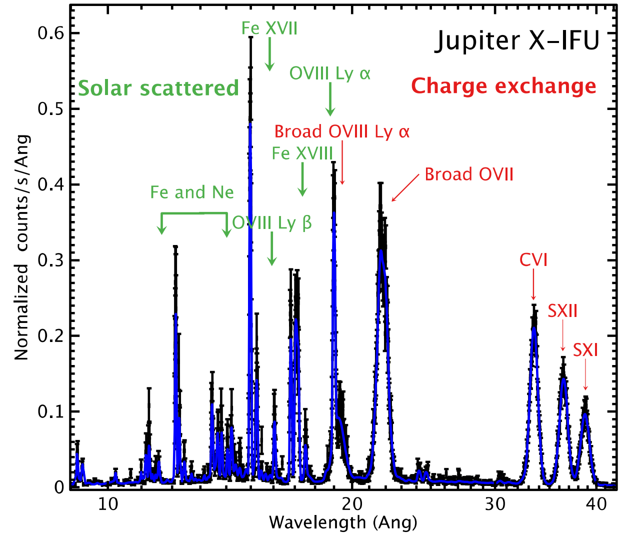
- Only extreme AGN expected in opt/IR surveys.
- X-rays needed to find the "average" AGN.

#ATHENANuggets by A.Comastri, G.Lanzuisi & J.Aird

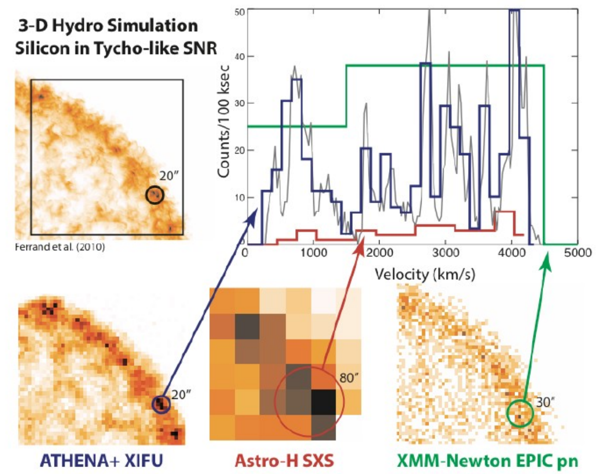
Observatory Science – All Corners of Astrophysics

- Planets and solar system bodies
- Exoplanets: magnetic interplay
- Star formation, brown dwarfs
- Massive stars: mass loss
- Supernovae: explosion mechanisms
- Supernova remnants: shock physics
- Stellar endpoints (NS)
- Interstellar medium

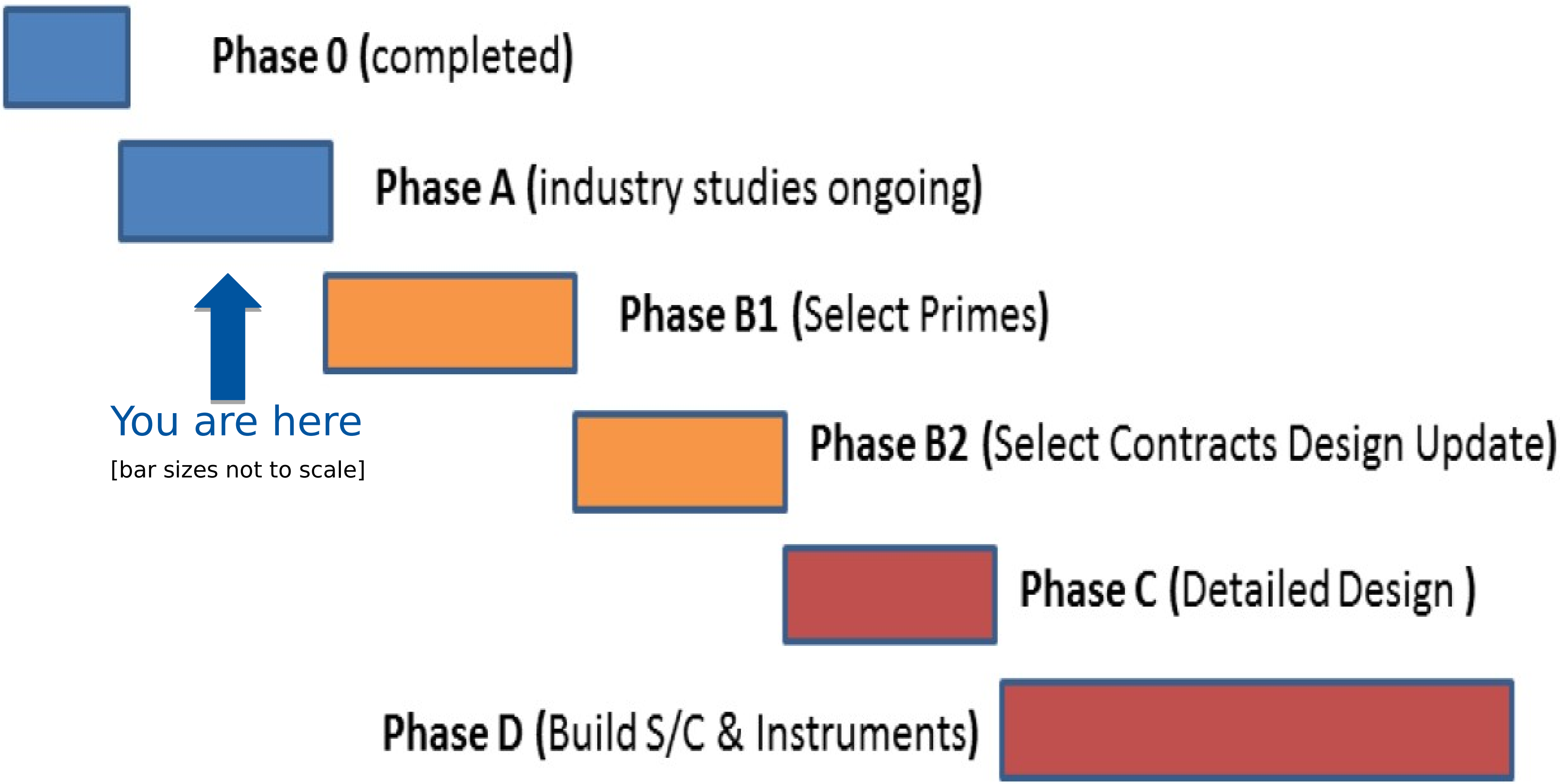
Branduardi-R+ (2013), Sciortino+ (2013)



Decourchelle, Costantini+ (2013), Motch+ (2013)

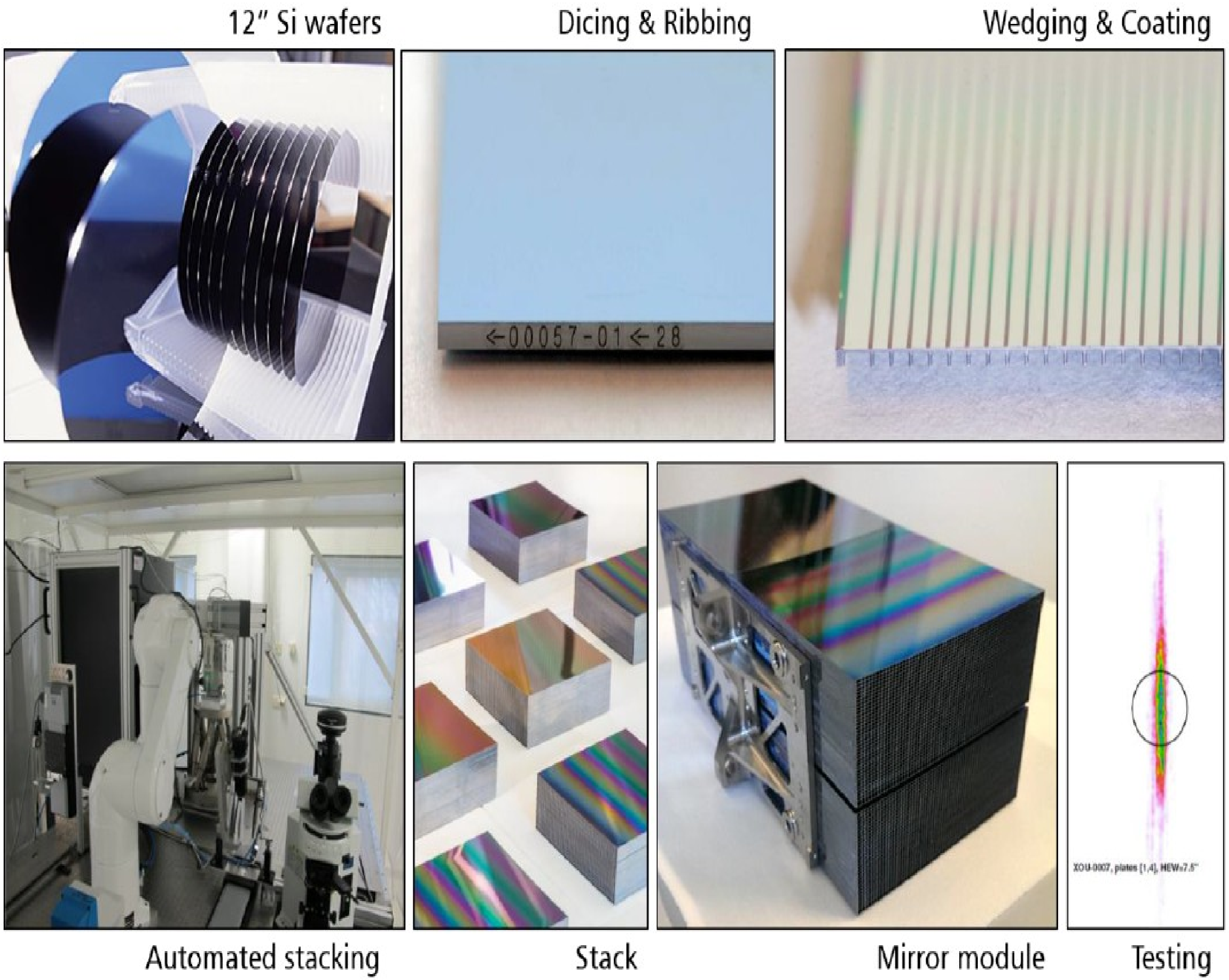


ATHENA Overall Schedule

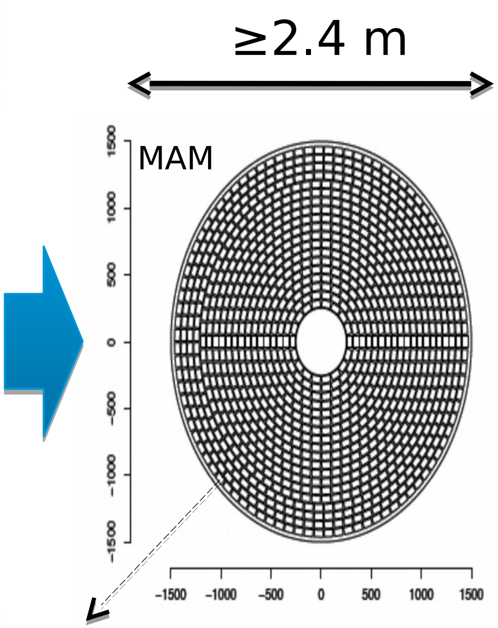


Key date: adoption by the ESA Science Program Committee, **2020**

Silicon Pore Optics (SPOs)



Edge-on zoom of a partial stack



Mirror module (~10^3 in the MAM)

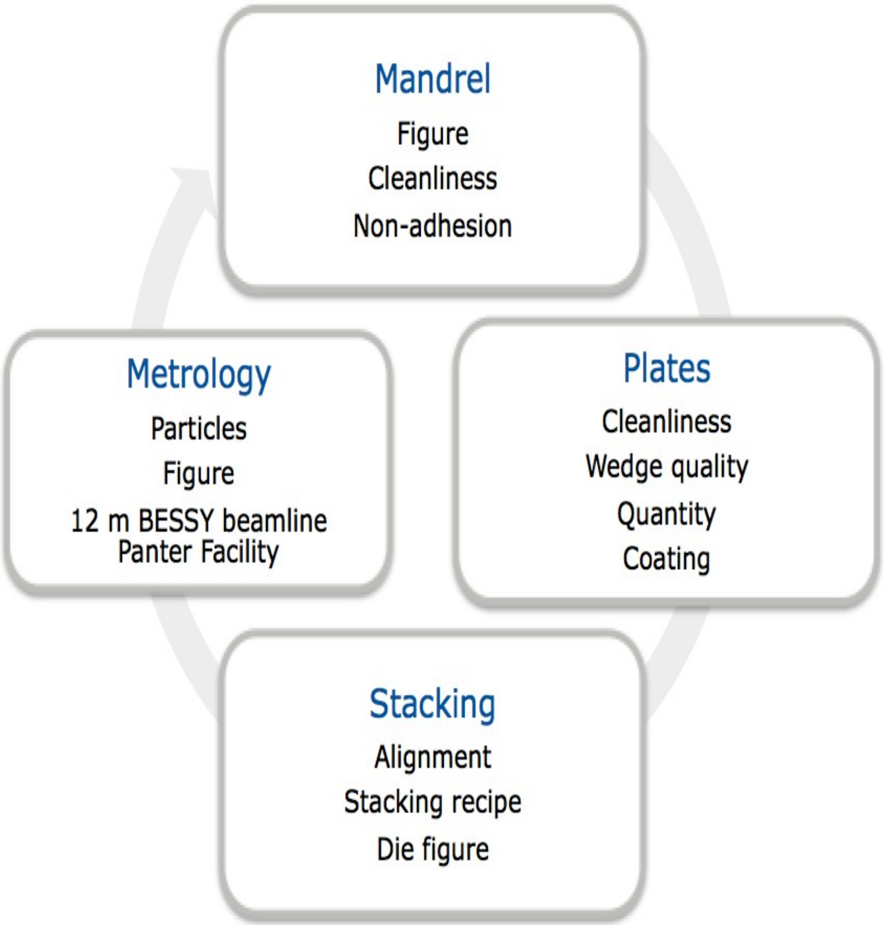
Collon+ (2016)

SPO Development Priority Activities

1. **Improving the angular resolution**
   - Deposition of first and second plate
   - Optimized die design for different radii
   - Stacking recipe (pressure, duration)

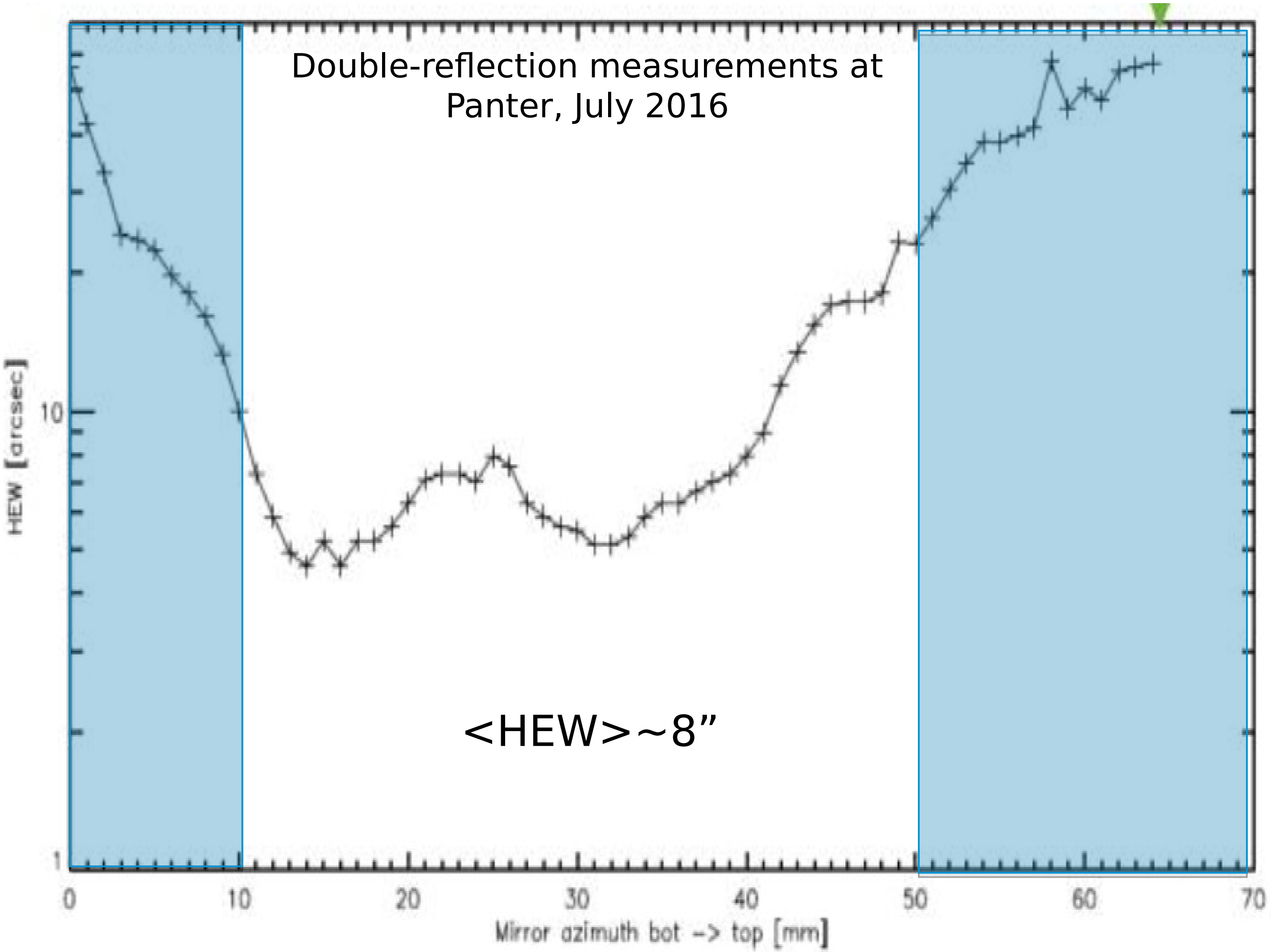
2. **Increasing production rates**
   - Mirror plate production automation
   - Coating mass production
   - Stacking time reduction

3. **Environmental qualification**
   - Annealing of stacks
   - Shock and vibration testing on stack level
   - Qualification and acceptance criteria definition



Bavdaz+ (2016)

HEW per column (entire pair of stacks in ~Wolter I configuration)



- <HEW>:~22” in 2015 → 13.9” in 2016.
- 60% of the optics have a HEW of 8”.
- Best performance: ~5”.
- Consistent results at BESSY (2.8 keV) and Panter (1.49 keV).

Collon+ (2016)

Summary

- ATHENA will be a transformational X-ray observatory designed to address the Hot and Energetic Universe science theme, and will impact virtually every corner of astronomy.
- ATHENA will represent a ≥order-of-magnitude performance improvement (in several parameter spaces) with respect to any existing or approved X-ray mission.
- Unique combination of effective area, spectral resolution *and* FoV.
- The Phase A study has confirmed technical feasibility, with a maturity level adequate to the current Study phase.
- Currently optimizing the mission profile/performance/international contributions to fit the cost cap.
- Intense SPO optics development, instrument optimization currently underway.

EXTRAS

Missing baryons: the WHIM

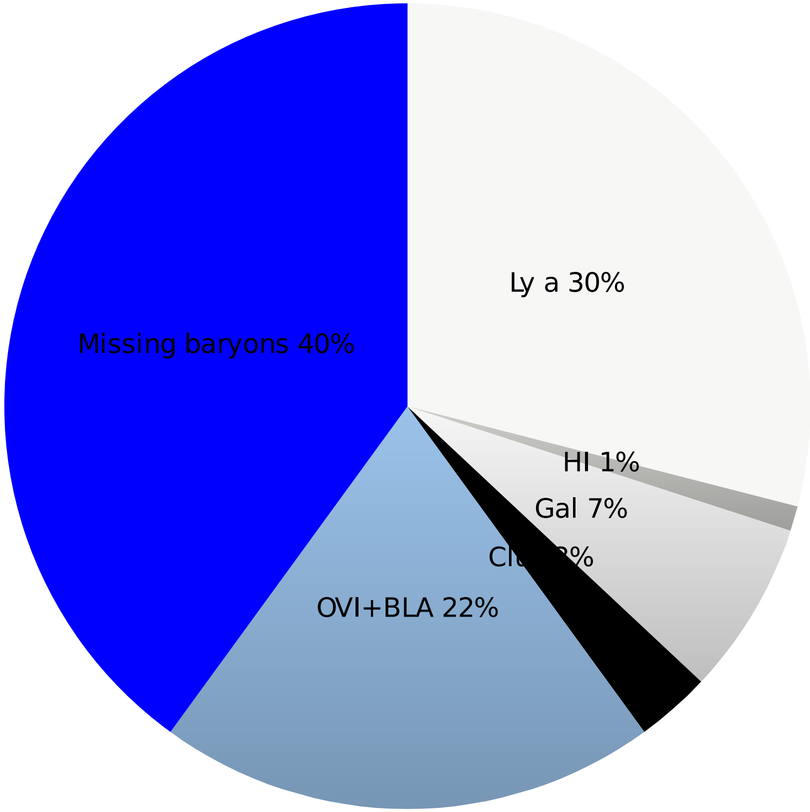
Cosmological hydro simulations show ~40% of baryons at **$T \sim 10^5$-10^7** K in the IGM.

- Unvirialised, shock heated and filamentary distribution

Potentially detectable through absorption/emission from ionised species.

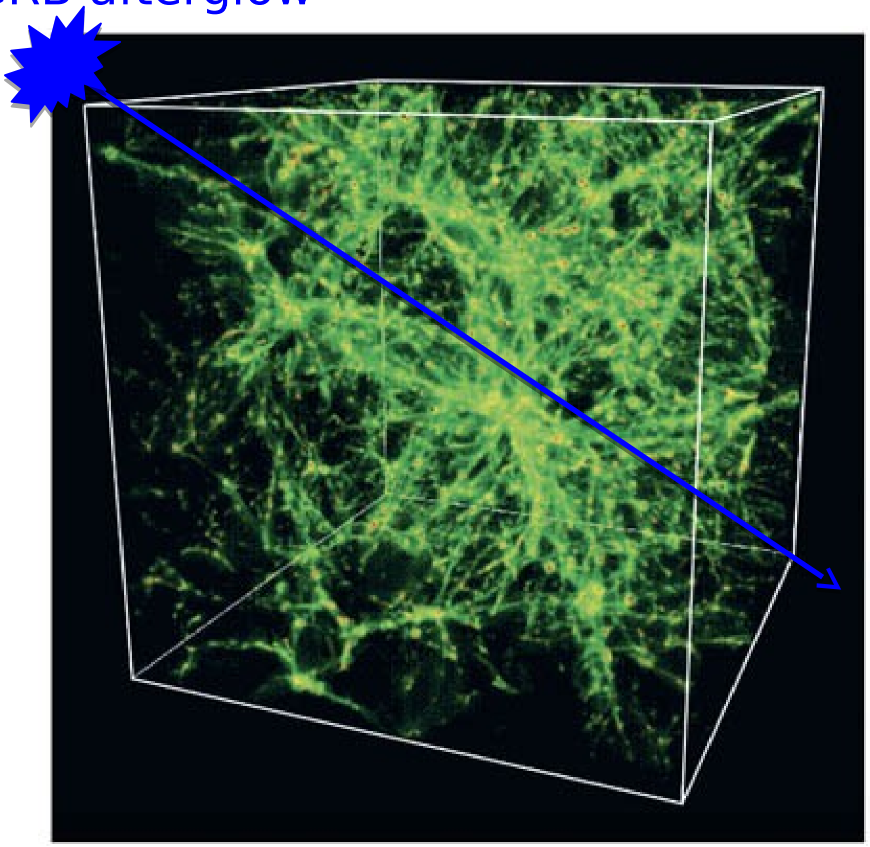
Note that:

- Mass and metals not necessarily in the same place
- Circum-galactic medium also contributes to emission/absorption



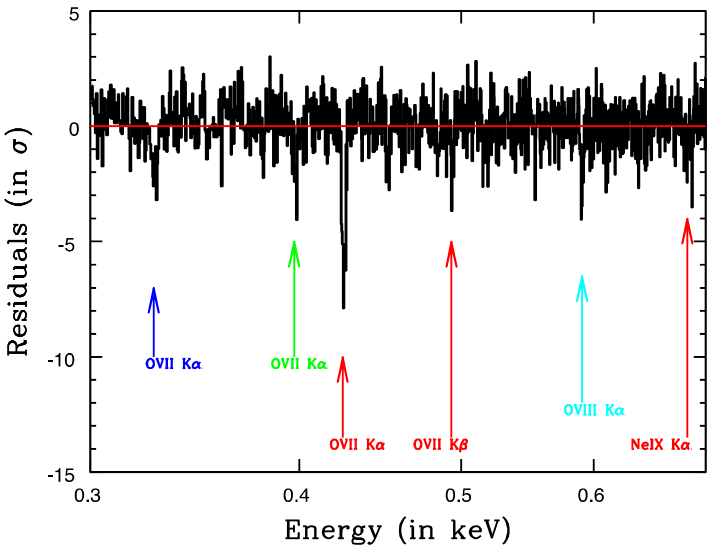
Characterising the WHIM baryons

AGN or
GRB afterglow



Cen & Ostriker 2006

WHIM filaments against a 10% brightest GRB afterglow



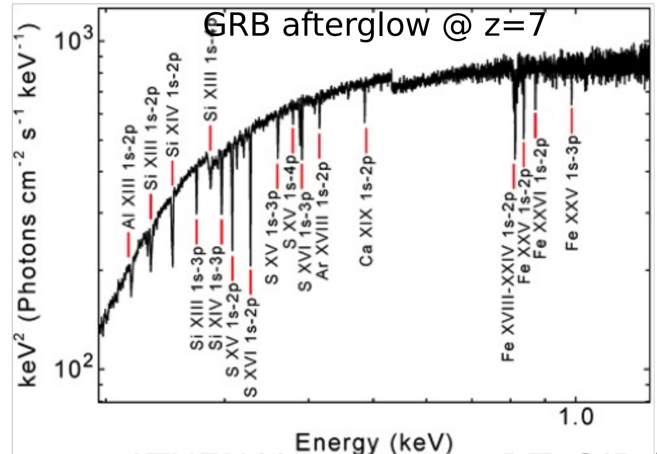
Barret et al. 2016, SPIE
Courtesy: F. Nicastro

Luminous extragalactic transients

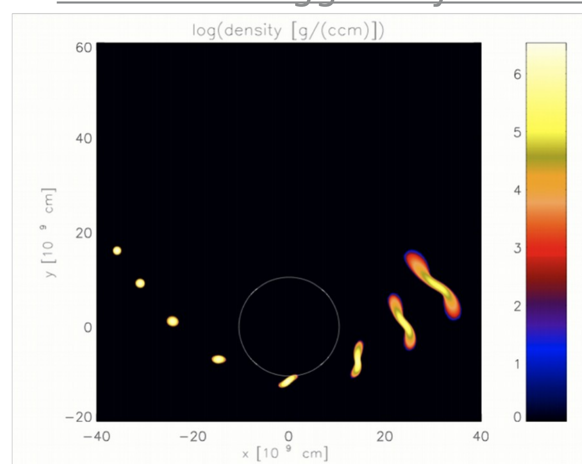
ATHENA will offer a quick Target of Opportunity facility, whereby a triggered observation could start in 4 hours ~40% of the cases.

High-z GRB afterglows will reveal the ISM composition at z~7-10

- Tidal Disruption Events (TDEs) result from the destruction of a star by a SMBH.
- Enormous potential for SKA discoveries & study of jetted TDEs (Donnarumma & Rossi)
- ATHENA will
  - Unveil SMBH through this
  - Reveal the composition of the outflowing material
  - Test for the presence of binary SMBH



#ATHENANuggets by P.T. O'Brien



Jonker, O'Brien et al. 2013: arXiv 1306.2336

#ATHENANuggets by P.Jonker

MCR+ Delta (Δ) MCR – Technical Notes

Mission Consolidation Review (May 2016) + Delta MCR (Feb. 2017)

Main technical conclusions:

- Mature mid-Phase A spacecraft design for all elements.
- Mass constraint (7 tons) can be achieved with *at most* a minor reduction of the mirror diameter (~7% effective area @1 keV).
- High-load at the center of the mirror structure is a potential concern, but can be addressed with reliable technical solutions.
- Complex SIM thermal control design, with high-level of dissipation (~3 kW) and ~no growth potential.
- X-IFU thermal budget and instruments' mass budgets to be consolidated.
- Launcher requirements still under definition (potential uncertainty).

MCR + ΔMCR – Cost Notes

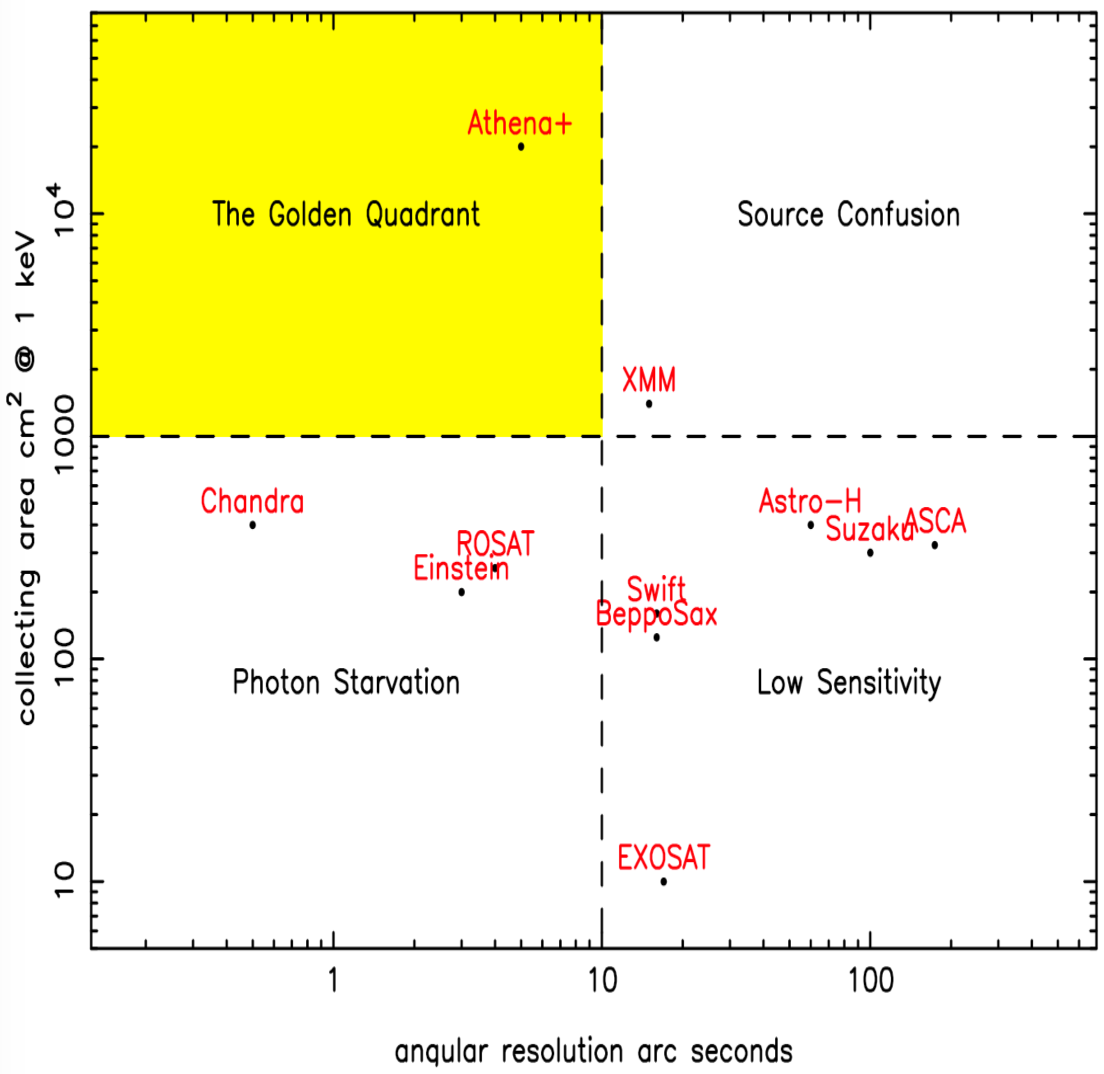
ESA Cost-at-Completion (CaC) cap: 1.05x10⁹ €

- Cost estimates systematically exceed the CaC cap over the whole Phase A.

- Envelope of international contributions (JAXA/NASA) defined, unlikely to change significantly.

- The problem *must be addressed* ≤autumn 2017. Among the possible options:
  - More "aggressive" industrial cost policy
  - Transfer of SIM-related activities/responsibility from ESA → others
  - Saving in operation (MOC/SOC) costs
  - Optimization of international contributions and/or new partners
  - Mission performance: mirror diameter/number of modules, field-of-regard, nominal operational life

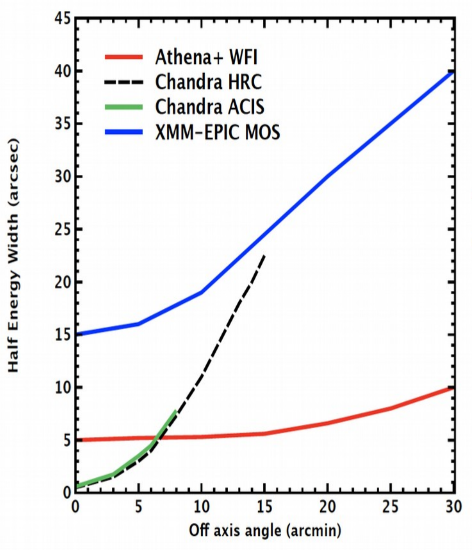
ATHENA mirror: a gold standard



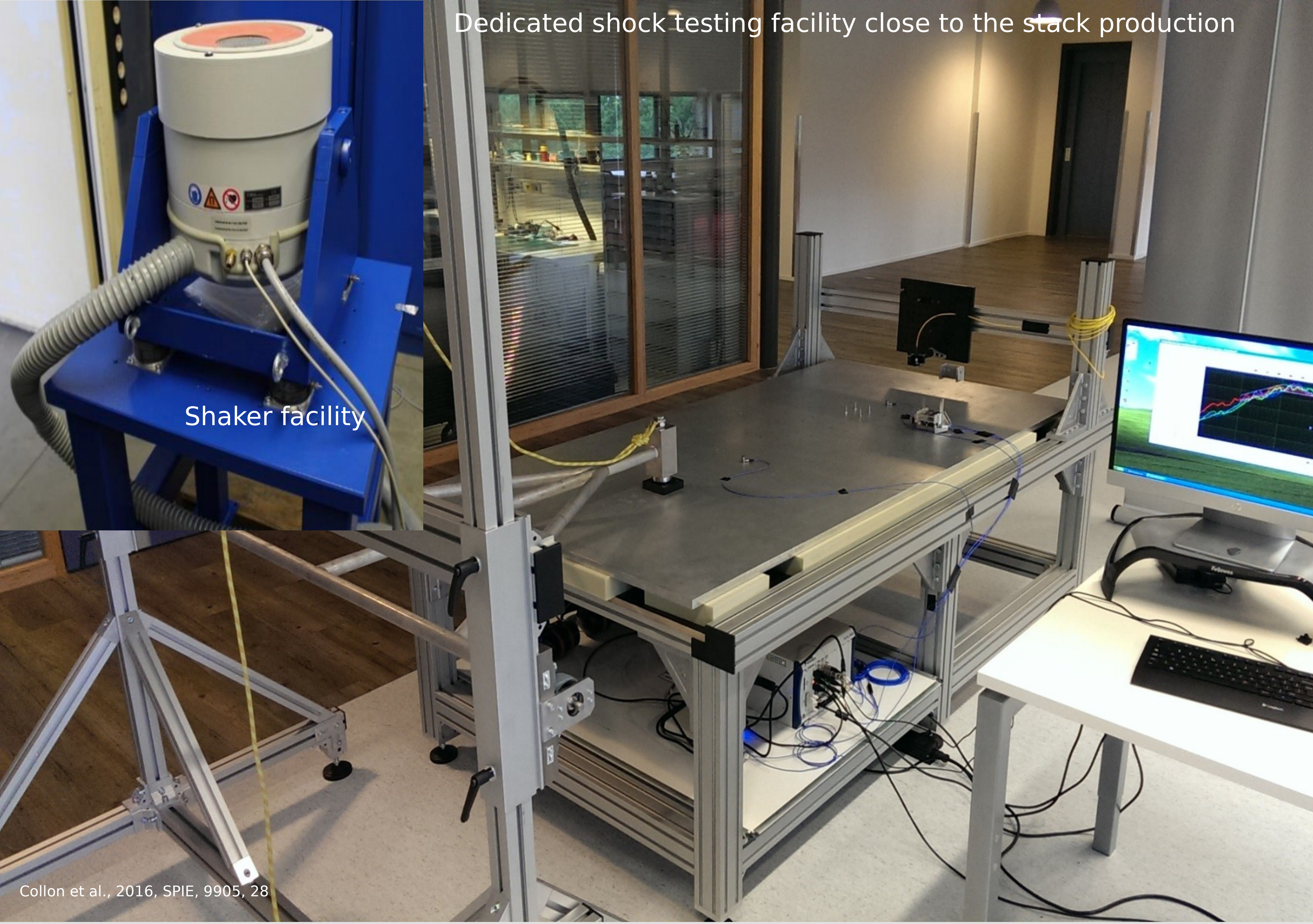
Willingale et al, 2013, arXiv:1307.1709

Key requirements:

- 1.4-2 m² area @1 keV
- 5” HEW on-axis
- Graceful degradation off-axis (<10” @20’)
- Limited vignetting @1 keV



Dedicated shock testing facility close to the stack production



Collon et al., 2016, SPIE, 9905, 28